

# Exploring the cosmic dark ages with the next generation of space and ground-based facilities

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## ABSTRACT

This paper reviews our current understanding of the process of re-ionization of the Universe, focusing especially on those models where re-ionization is caused by UV radiation from massive stars. After reviewing the expected properties of stars at zero metallicity, I discuss the properties of primordial HII regions and their observability.

**Keywords:** Cosmology, NGST, large ground based telescopes, reionization

## 1. INTRODUCTION

The emergence of the first sources of light in the Universe and the subsequent re-ionization of hydrogen marks the end of the "Dark Ages" in cosmic history, a period characterized by the absence of discrete sources of light. Despite its remote timeline, this epoch is currently under intense theoretical investigation and will soon begin to be probed observationally. The first reason to study this epoch is the fact that this - together with the epoch of recombination - is the most accessible of the global phase transitions undergone by the Universe after the Big Bang.

Two facts make the formation of structure in the Dark Ages easier to study theoretically than similar processes occurring at other epochs: *i)* the formation of the first structures is directly linked to the growth of linear perturbations, and *ii)* these objects have a known metallicity set by the end-product of the primordial nucleosynthesis. Therefore, the second reason to study this epoch is because it makes it possible to probe the power spectrum of density fluctuations emerging from recombination at scales smaller than accessible by current cosmic microwave background experiments.

In a Universe where structures grow hierarchically, the first sources of light act as seeds for the subsequent formation of larger objects. Thus, the third reason to study this period is that by doing so we may learn about processes relevant to the formation of the nuclei of present day giant galaxies.

In Section 2, I will review our present view on the basic processes leading to re-ionization. I refer the reader to the recent review by Loeb and Barkana<sup>?</sup> for a more detailed discussion. In Section 3, I will review in more detail a few recent theoretical results relevant to the case of re-ionization by stellar UV radiation. The present observational status is summarized in Section 4. The properties of primordial and low metallicity HII regions are discussed in Sections 5 and 6, respectively. Finally, in Section 7, I address the observability of these objects by NGST and future large ground-based telescopes.

## 2. THE BASIC PROCESSES LEADING TO RE-IONIZATION

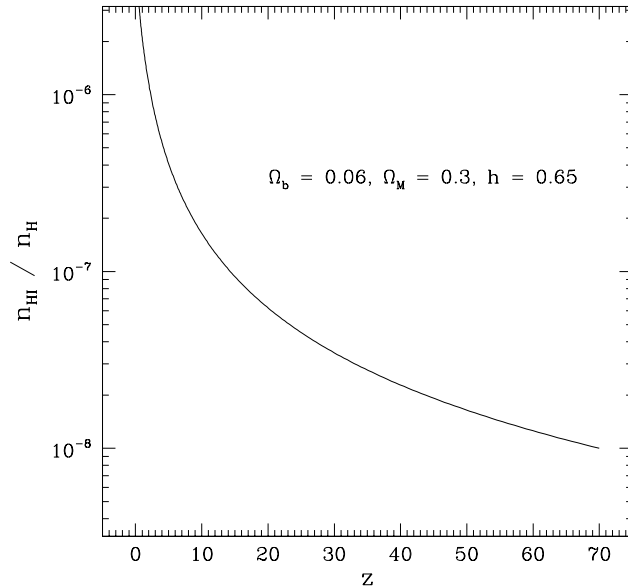
In the standard Cold Dark Matter (CDM) cosmology galaxies are assembled through hierarchical merging of building blocks with smaller mass. The first such building blocks, with  $M \gtrsim 10^4 M_\odot$ ,<sup>?, ?, ?, ?, ?</sup> form in various CDM models at  $z \gtrsim 15$ .

While we do not know whether the first sources of light are powered by nuclear energy from fusion reactions or by gravitational accretion,<sup>?</sup> it is often believed that population III stars are responsible for the re-ionization of hydrogen<sup>?</sup> at  $z \simeq 6-20$ ,<sup>?, ?, ?</sup> while the harder UV spectrum of AGNs is responsible for the re-ionization of helium<sup>?</sup> at lower redshift.

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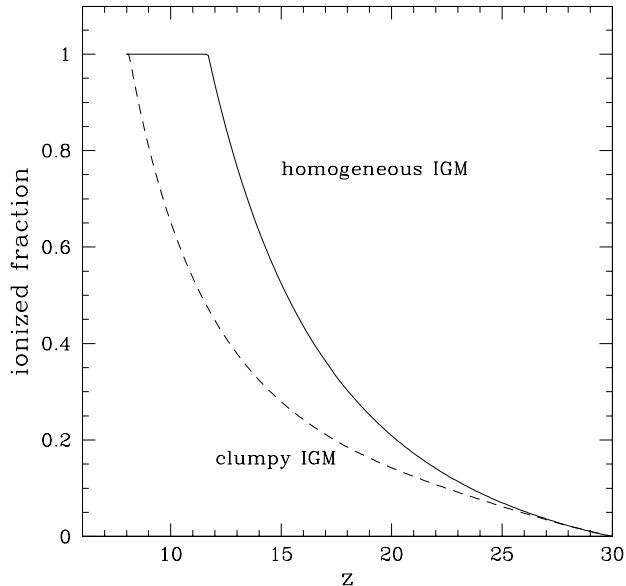


**Figure 1.** The fraction of neutral hydrogen needed to produce an average  $\tau = 1$  shortwards of Lyman  $\alpha$  is shown as a function of redshift. The plot is valid for a uniform IGM. Only a small fraction of neutral hydrogen along the line of sight would be sufficient to produce significant opacity.

The following simple calculation shows that nuclear processing of only a very small fraction of baryons would be sufficient to re-ionize the Universe.<sup>?</sup> Fusion of hydrogen releases 7 MeV per proton but only 13.6 eV are needed to ionize hydrogen. Thus, a fraction  $2 \times 10^{-6}$  of hydrogen undergoing fusion is energetically sufficient to re-ionize all hydrogen. In practice, the minimum fraction will be larger by a factor ten to one hundred because not all energy is released in the form of ionizing photons, not all ionizing photons successfully escape from the sources into the IGM, and recombinations increase the required number of ionizing photons. All these factors depend on the details of the process and have large uncertainties. By assuming that the minimum fraction is 30 times the value given above, i.e.,  $6 \times 10^{-5}$  and a yield of  $\sim 0.3 M_{\odot}$  of metals produced per  $M_{\odot}$  of hydrogen processed in a massive star,<sup>?,?</sup> one can estimate that the minimum mean metallicity of the Universe at re-ionization was  $\sim 10^{-3} Z_{\odot}$ .

If the power source for re-ionization is not nuclear fusion but rather gravitational accretion onto massive black holes, a smaller fraction of material needs to be processed thanks to the higher efficiency of gravitational accretion. Clearly this scenario does not place any constraint on the metallicity of the Universe at re-ionization and leaves unanswered the question of the origin of the black holes (primordial or stellar). Even if re-ionization is caused by stellar UV radiation, it is natural to expect that some fraction of these stars will leave black holes as remnants.<sup>?</sup> Thus, in both scenarios, we expect that some seed black holes will be present at the end of re-ionization, with interesting implications on the formation of AGNs and galaxies.<sup>?,?</sup>

Even though we often refer to re-ionization as if it was a sudden transition, the time elapsed between the epochs when 10 % and 90 % of hydrogen was re-ionized can last a significant fraction of the age of the Universe at re-ionization: thus, the dark ages may end with an extended twilight. Inhomogeneities along the line of sight may create a dispersion in optical depth shortwards of Lyman  $\alpha$ . Moreover, only a very low residual fraction



**Figure 2.** The fraction of ionized hydrogen as a function of redshift for a Madau et al.<sup>?</sup> star formation rate extrapolated to  $z=30$ . The solid line applies to the case of a uniform IGM while the dashed line represents a clumpy IGM with clumpiness parameter  $C=10$  (see text).

of neutral hydrogen is needed to produce a Gunn-Peterson trough in the spectra of high redshift quasars. To illustrate this I give in Figure 1, as a function of redshift, the fraction of neutral hydrogen required to have a Gunn-Peterson optical depth of one in a uniform IGM.<sup>?,?</sup> It should be noted that in analogy to the proximity effect in QSOs<sup>?</sup> the opacity near Lyman  $\alpha$  would be modified in the neighborhood of ionizing sources.<sup>?</sup> In order to obviate the problem of the extreme sensitivity of the Gunn-Peterson trough to even a very small residual fraction of neutral hydrogen, methods are being considered that rely on the study of the microwave background polarization.<sup>?</sup>

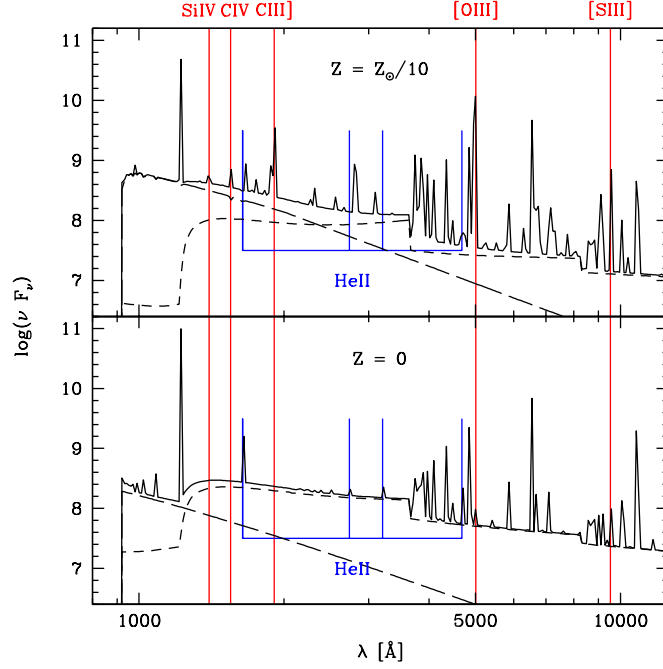
In the following I will assume that re-ionization is due to massive stars and explore the theoretical and observational consequences of this assumption.

### 3. RE-IONIZATION BY STELLAR UV RADIATION : SOME THEORETICAL CONSIDERATIONS

If re-ionization of hydrogen is caused by massive stars, the details of the process and its consequences for the metal enrichment of the Universe depend on the properties of these objects and on how metals and UV radiation escape into the IGM. Below, I will briefly review present ideas on some of these issues.

#### 3.1. Which stars?

The standard picture is that, at zero metallicity, cooling is dominated by the less effective  $H_2$  cooling and leads to the formation of very massive objects, with masses exceeding  $100 M_\odot$ .<sup>?,?</sup> The spectral energy distribution



**Figure 3.** The synthetic spectrum of a zero-metallicity HII region (bottom panel) is compared to that of an HII region with  $Z = 0.1 Z_{\odot}$ . The long dashed lines represent the stellar continuum while the short dashed lines represent the nebular continuum. Note how the latter dominates the continuum in the zero-metallicity case.

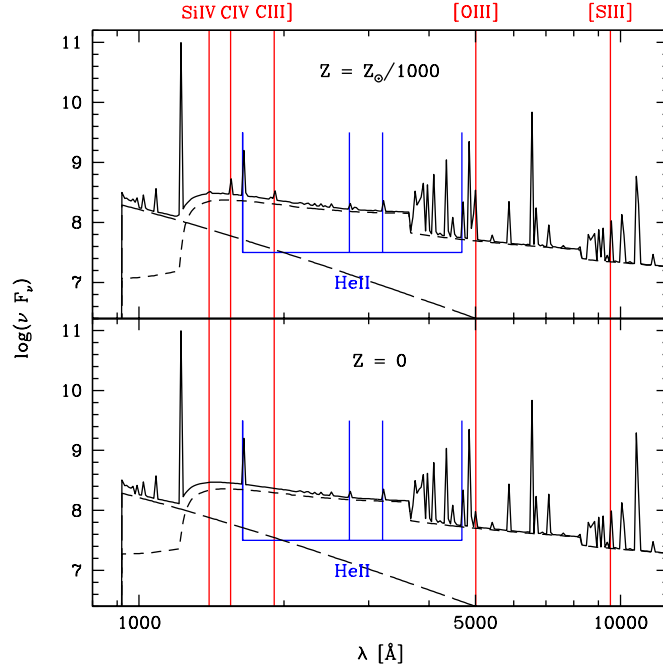
(SED) of these massive stars resembles that of a black body with an effective temperature around  $10^5$  K.<sup>?</sup> Due to their high temperatures, these stars are very effective in ionizing hydrogen and helium.

It should be noted that, even at lower mass, zero-metallicity stars are expected to be much hotter than their solar metallicity analogues.<sup>?</sup> By assuming that only massive stars are present, one finds that roughly  $\sim 10^{-4}$  of baryons need to be incorporated into stars in order to re-ionize hydrogen,<sup>?</sup> in agreement with the estimates of Section 2.

The second generation of stars forming out of pre-enriched material will probably have different properties since molecular hydrogen can be dissociated by UV radiation of lower energy ( $\sim 11$  eV) than that required to ionize atomic hydrogen.<sup>?,?</sup> This implies that molecular hydrogen cannot be shielded by atomic hydrogen. However, the presence of some metals in the ISM opens up the possibility of having some shielding by dust. Various scenarios have been predicted for the second generation objects. If the metallicity is high enough ( $> 5 \times 10^{-4} Z_{\odot}$ ), cooling by metal lines is viable and one is likely to produce stars of lower mass.<sup>?</sup> On the other hand, if the metallicity is lower, halos with virial temperature greater than  $10^4$  K can cool via neutral atomic lines. Such systems may experience a build-up of  $H_2$  thanks to self-shielding and continue the formation of very massive stars.<sup>?</sup>

### 3.2. Which Initial Mass Function?

From the previous discussion it appears that in the zero-metallicity case one should expect a very top heavy Initial Mass Function (IMF). It is less clear whether the second generation of stars is also top-heavy or characterized by a more normal IMF. In practice, it is wise to consider both possibilities.



**Figure 4.** The synthetic spectrum of a zero-metallicity HII region (bottom panel) is compared to that of an HII region with  $Z = 10^{-3}Z_{\odot}$ . The long dashed lines represent the stellar continuum while the short dashed lines represent the nebular continuum. Note how the latter dominates the continuum in both cases.

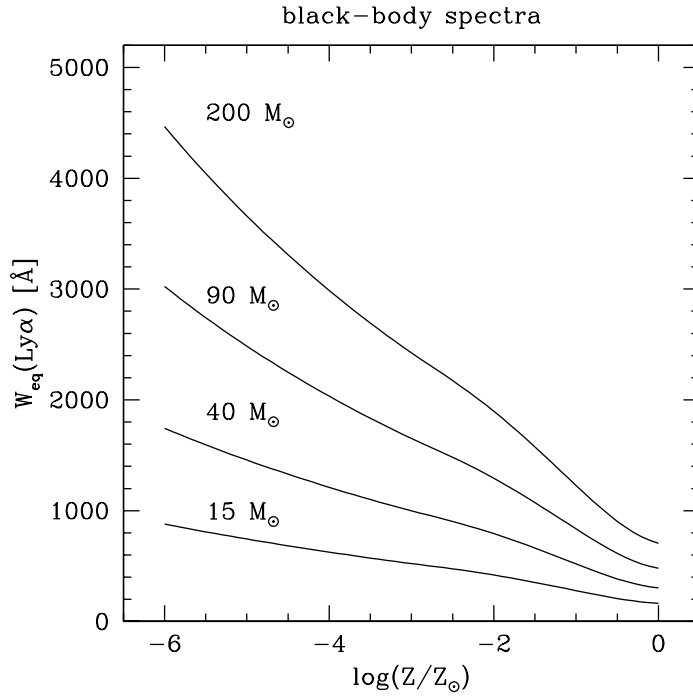
### 3.3. What about re-combinations?

The number of UV photons needed to re-ionize the Universe depends on the rate of hydrogen recombination. Recombinations are not very important if the medium is homogeneous. However, inhomogeneities increase locally the density and therefore can increase dramatically the recombination rate which is proportional to the square of the local density. The basic features of this effect can be captured by a simple model.<sup>?</sup> In Figure 2 I have considered the star formation rate (SFR) given by Madau et al.<sup>?</sup> extrapolated to  $z=30$ . Assuming this SFR and a uniform IGM, the Universe would reionize at  $z_r = 11.7$  and recombinations would increase the required number of ionizing photons by only 28 % relative to the case without recombination. The same star formation history in a Universe with a clumpiness factor<sup>?</sup>  $C \equiv \langle n_H^2 \rangle / \langle n_H \rangle^2 = 10$  would re-ionize hydrogen at  $z_r = 8.1$ , with on average 3.4 photons required to produce a single re-ionization. These results do not depend critically on the specific starting redshift.

It is possible to calculate in more detail the amount of inhomogeneity.<sup>?</sup> As an example, it has been argued that if re-ionization occurs at  $z_r < 20$  a significant fraction of mini-halos ( $\sim 10^4 M_{\odot}$ ) will be able to collapse and, in the process of being photo-evaporated, act as significant sinks of UV radiation.<sup>?,?</sup> The net effect of an increased recombination rate will be a higher mean metallicity of the Universe at re-ionization, perhaps by a factor 3.

### 3.4. What about the escape of UV radiation?

If the first generation stars forms within more massive objects only a fraction of their UV radiation may be able to escape. For local disk galaxies the escape fraction is probably of only  $\lesssim 10\%$ .<sup>?,?,?</sup> The estimate for high redshift galaxies could be as high as 50 %<sup>?</sup> but could be lower if UV-grey dust is present in the sample.<sup>?</sup> If



**Figure 5.** Lyman  $\alpha$  equivalent widths for HII regions ionized by stars with a range of masses and metallicities. The results obtained for black bodies or stellar atmospheres are very similar.

only a fraction of UV radiation escapes from the first objects this implies once again that the mean metallicity of the Universe will be higher if stars are the relevant UV sources.

### 3.5. How is the Inter Galactic Medium enriched?

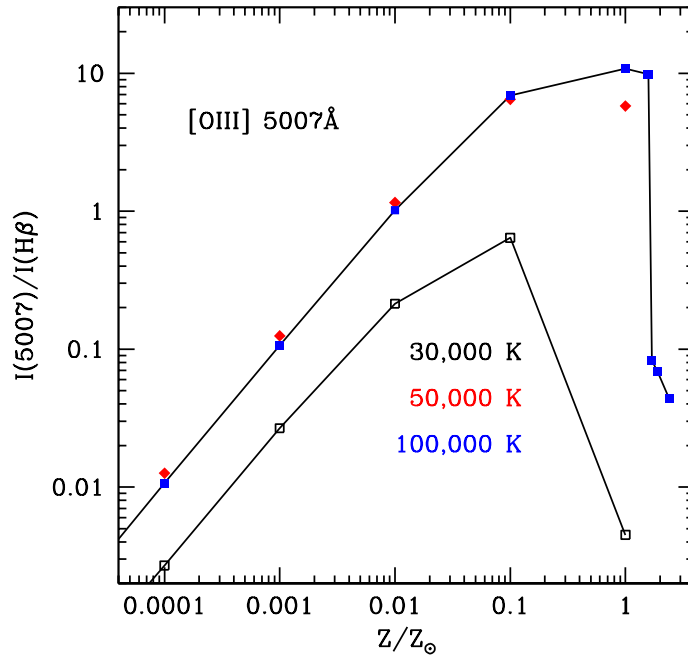
When considering the mean metallicity of the Universe at re-ionization, we have been referring to the total amount of metals produced. This is in general very different from the metallicity actually measured in the Inter-Galactic Medium (IGM). If population III stars are formed in halos of sufficiently low mass they can enrich the IGM by SN-driven winds.<sup>?, ?</sup> When a halo undergoes a SN-driven outflow, the ejection of metals can be very effective. However, it is not clear how effective this process is when averaged over all halos.

Note that if the escape fractions of UV radiation and metals are comparable, we should expect a mean metallicity of the IGM at re-ionization similar to the minimum mean metallicity of the Universe,  $Z \simeq 10^{-3} Z_{\odot}$  (see Sect 2). This is broadly consistent with the metallicity of damped Lyman  $\alpha$  systems which is higher than  $10^{-3} Z_{\odot}$  for  $z < 4$ .<sup>?</sup>

### 3.6. Remnants and signature of a population III

A fraction of the supermassive stars produced at zero metallicity may leave massive black holes as remnants.<sup>?</sup> It has been argued that under a reasonable assumption the mass density of these black holes may be comparable to that of the supermassive black holes observed locally in the cores of giant galaxies.<sup>?</sup> This opens up the interesting possibility that the supermassive black holes are formed by merging of the population III remnants.

Population III objects are characterized by nucleosynthetic patterns different from those produced by ordinary stars.<sup>?, ?</sup> In principle, such patterns could be identified by studying low metallicity objects at low redshift



**Figure 6.** The ratio  $[OIII]\lambda 5007 / H\beta$  is plotted as a function of metallicity for three different effective temperatures: 30,000K (open squares and bottom line), 50,000K (solid diamonds), and 100,000K (solid squares and top line).

but possible contamination throughout cosmic history makes this measurements difficult to interpret. Thus, it may be better to look for population III signatures in the Lyman  $\alpha$  forest absorbers at high redshift.

#### 4. PRESENT OBSERVATIONAL STATUS

The most direct observational evidence of re-ionization is the detection of a Gunn-Peterson trough<sup>?</sup> in the spectrum of high redshift quasars. Neutral hydrogen clouds along the line of sight (the Lyman  $\alpha$  forest) produce increasing absorption as the redshift increases. Still, even at  $z \simeq 5$  some signal is detected below Lyman  $\alpha$ , suggesting that re-ionization occurs at higher redshifts.

Recently, the Sloan Digital Sky Survey has began detecting large numbers of high redshift quasars, including a few around  $z \simeq 6$ .<sup>?</sup> QSO SDSSp J103027.10 055245.0 at  $z = 6.28$  shows a drop in continuum flux below Lyman  $\alpha$  by a factor 150. Other QSOs at slightly lower redshift show a much smaller continuum drop. Thus, it has been suggested that a Gunn-Peterson trough has been detected in this object.<sup>?, ?</sup>

On the basis of the qualitative arguments given in Sect 2, it is clear that it is hard to make a statement regarding re-ionization on the basis of a single object. However, this detection opens up the possibility that re-ionization occurs at a relatively low redshift, thus making it more easily accessible to observations.

Unlike hydrogen re-ionization, that of helium has been already firmly identified from the detection of a Gunn-Peterson trough.<sup>?, ?, ?</sup> Due to the higher photon energy required to re-ionize helium, it is often assumed that it is caused by the harder UV radiations from AGN.

## 5. PRIMORDIAL HII REGIONS

Two direct consequences of the high effective temperature of zero-metallicity stars are their effectiveness in ionizing hydrogen (and helium) and their low optical-to-UV fluxes. Both tend to make the direct detection of the stellar continuum much harder than the detection of the associated HII region.

In Panagia et al.<sup>?</sup> we report on our calculations using Cloudy90<sup>?</sup> of the properties of these HII regions (see also Figure 3.) We find that the electron temperatures is in excess of 20,000 K and that 45 % of the total luminosity is emitted by the HII region in the Lyman  $\alpha$  line, resulting in a Lyman  $\alpha$  equivalent width (EW) of 3000 Å.<sup>?</sup> The helium lines are also rather strong, with the intensity of HeII  $\lambda$ 1640 comparable to that of H $\beta$ .<sup>?</sup>

An interesting feature of these models is that the emission longward of Lyman  $\alpha$  is dominated by a strong two-photon nebular continuum. The H $\alpha$ /H $\beta$  ratio for these models is 3.2. Both the red continuum and the high H $\alpha$ /H $\beta$  ratio could be naively (and incorrectly) interpreted as a consequence of dust extinction even though no dust is present in these systems.

From the observational point of view one will generally be unable to measure a zero-metallicity but will usually be able to place an upper limit on it. When would such an upper limit be indicative that one is dealing with a population III object? On the basis of the arguments in the previous sections it is reasonable to argue that a metallicity  $Z \simeq 10^{-3} Z_{\odot}$  can be used as a dividing line between the pre and post re-ionization Universe. A similar value is obtained by considering that the first supernova (SN) going off in a primordial cloud with a mass of  $10^6 M_{\odot}$  will pollute it to a metallicity of  $\sim 0.5 \times 10^{-3} Z_{\odot}$ .<sup>?</sup> Computing the number of SNaE required to unbind the ISM in a primordial cloud provides an independent - and higher - value for the metallicity,  $Z \simeq 10^{-2} Z_{\odot}$ .<sup>?</sup> Thus, any object with a metallicity higher than  $\sim 10^{-3} Z_{\odot}$  is not a true first generation object.

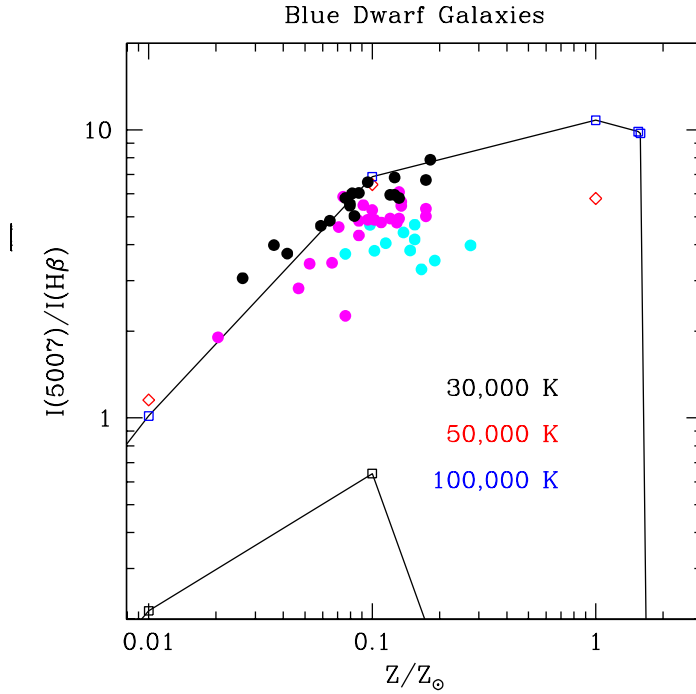
## 6. LOW METALLICITY HII REGIONS

In order to distinguish a zero-metallicity HII region from one with very low, but non-zero, metallicity we need to compute the properties of the latter objects. We have carried out such an analysis for metallicity down to  $10^{-6} Z_{\odot}$ .<sup>?</sup> using a combination of Cloudy90<sup>?</sup> and analytical calculations. In Figure 4 the synthetic spectrum of an HII region with metallicity  $10^{-3} Z_{\odot}$  is compared to that of an object with zero metallicity. The two are very similar except for a few weak metal lines with the strongest one being the [OIII] $\lambda$ 5007 line. In Figure 5 we show the Lyman  $\alpha$  EWs for individual HII regions ionized by stars with different masses and metallicities. Values of EW in excess of 1,000 are possible already for objects with metallicity  $\sim 10^{-3} Z_{\odot}$ . This is particularly interesting given that Lyman  $\alpha$  emitters with large EW have been identified at  $z=5.6$ .<sup>?</sup> and possibly at even higher redshift.<sup>?</sup>

Even though the metal lines at these metallicities are weak, some of them can be used as metallicity tracers. In Figure 6 the ratio of the intensity of [OIII] $\lambda$ 5007 to H $\beta$  is plotted for a range of stellar temperatures and metallicities. It is immediately apparent that for  $Z < 10^{-1} Z_{\odot}$  this line ratio traces metallicity linearly (for each individual star.) Our reference value  $Z = 10^{-3}$  corresponds to a ratio [OIII]/H $\beta$  = 0.1. The weak dependence on mass ensures that this ratio remains an excellent indicator of metallicity also when one considers the integrated signal from a population with a range of stellar masses. The validity of these conclusions is confirmed by comparing the model predictions to the properties of blue dwarf galaxies (see Figure 7).

Another difference between zero-metallicity and low-metallicity HII regions lies in the possibility that the latter may contain dust. If dust can form at low metallicity as well as in the local Universe, for a  $Z = 10^{-3} Z_{\odot}$  HII region dust may absorb up to 30 % of the Lyman  $\alpha$  line, resulting in roughly 15 % of the energy being emitted in the far IR.<sup>?</sup>





**Figure 7.** Blue dwarf galaxies can be used to verify the theoretical calibration of  $[\text{OIII}]/\text{H}\beta$  as a metallicity indicator. Models derived for three different stellar masses are considered : 30,000K (open squares and bottom line), 50,000K (solid diamonds), and 100,000K (solid squares and top line). The black solid circles refer to dwarf galaxies with  $[\text{OIII}]\lambda 5007/[\text{OII}]\lambda 3727 > 5$ , the dark grey circles to dwarf galaxies with  $[\text{OIII}]/[\text{OII}]$  in the range 2.5-5, and the light grey circles to galaxies with  $[\text{OIII}]/[\text{OII}] < 2.5$ .

## 7. FUTURE FACILITIES

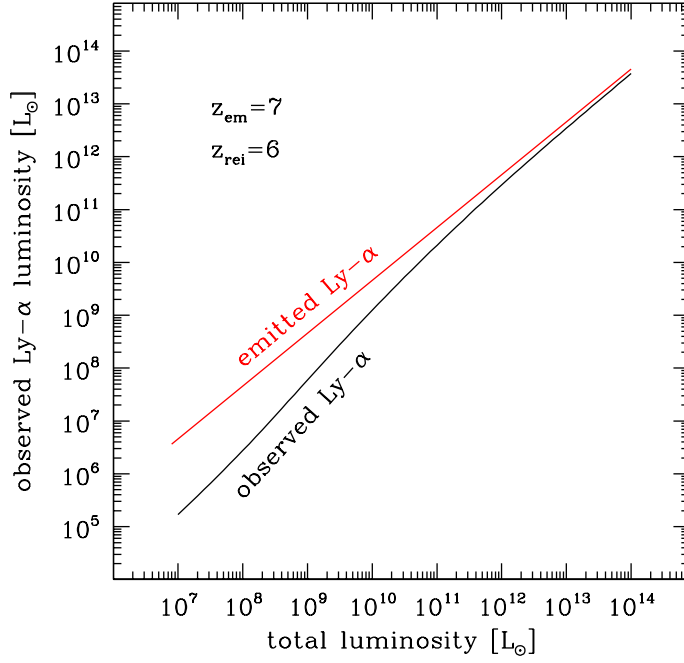
It is natural to wonder whether primordial HII regions will be observable with the generation of telescopes currently on the drawing boards. In this section, I will focus mostly on the capabilities of the Next Generation Space Telescope and of a 30m ground based telescope. However, before considering these facilities in detail it is necessary to estimate the effect of intergalactic absorption by neutral hydrogen.

### 7.1. The effect of intergalactic absorption

Intergalactic absorption by intervening neutral hydrogen will suppress Lyman  $\alpha$ .<sup>?, ?, ?</sup> A comparison of the observed vs emitted Lyman  $\alpha$  intensities is given in Figure 8. The transmitted Lyman  $\alpha$  flux depends on the total luminosity of the source since this determines the radius of the resulting Stroemgren sphere.<sup>?, ?</sup> This effect may explain the possible detection of Lyman  $\alpha$  at redshift greater<sup>?</sup> than that at which a Gunn-Peterson trough has been detected in quasars.<sup>?</sup> A Lyman  $\alpha$  luminosity of  $\sim 10^9 L_{\odot}$  corresponds to  $\sim 10^6 M_{\odot}$  of massive stars. In the following I will consider a star cluster of this luminosity.

### 7.2. Imaging

The synthetic spectra derived above can be convolved with a suitable filter response in order to obtain a spectral energy distribution that can be compared directly to the NGST imaging sensitivity for  $10^5$ s exposures (an example is shown in Figure 9). It is clear that NGST will be able to easily detect such objects. Due to



**Figure 8.** Transmitted Lyman  $\alpha$  intensity as a function of the object bolometric luminosity. Brighter objects re-ionize their neighborhood and are able to reduce the Lyman  $\alpha$  attenuation.

the high background from the ground, NGST will remain superior to 30m ground-based telescopes for these applications.

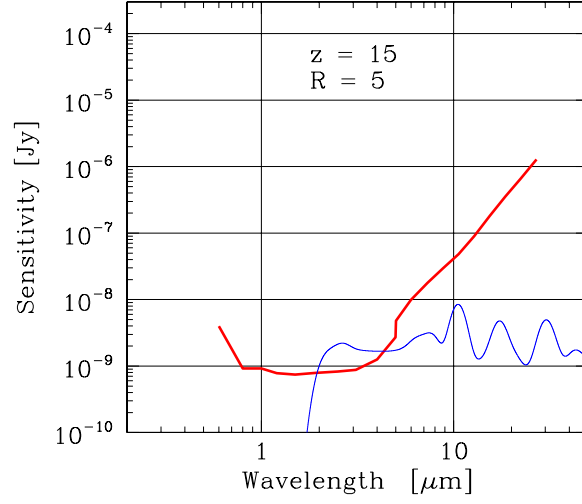
Scattering of Lyman  $\alpha$  photons around a source before re-ionization creates an extended ( $\sim 15$  arcsec at  $z=10$ ) halo<sup>?</sup> that is in principle detectable in narrow band imaging by NGST. Unfortunately, such a halo is over-resolved by NGST and would be detectable with  $S/N=10$  in a  $10^5$ s exposure only around an object with a Lyman  $\alpha$  luminosity of  $10^{12} L_{\odot}$ , *i.e.*, much brighter than the currently expected population III sources.

### 7.3. Spectroscopy

The synthetic spectra can also be compared to the NGST spectroscopic sensitivity for  $10^5$ s exposures (see Figure 10). NGST is able to detect lines from a  $10^6 M_{\odot}$  starburst (in massive stars) only at relatively low redshift. It will be possible to place interesting limits on the metallicity of these sources only if they are either at a lower redshift or brighter than assumed here.

Under somewhat special circumstances it may be possible to identify objects at redshift higher the re-ionization also through the combined signature of a Lyman  $\alpha$  and a Lyman  $\beta$  trough.<sup>?</sup> While potentially very interesting, this particular observations would not confirm that these objects are truly first generation.

Making spectroscopic observations at high spectral resolution ( $R \gtrsim 5000$ ) most of the sky background in the H band (most relevant for  $z \simeq 10-12$ ) can be reduced by a significant factor, so that the performance of a 30m ground based telescope operating between the OH lines would significantly exceed that of NGST. These telescopes would potentially be able to help us identify true first generation objects by placing strong upper limits on the intensity of metal lines.



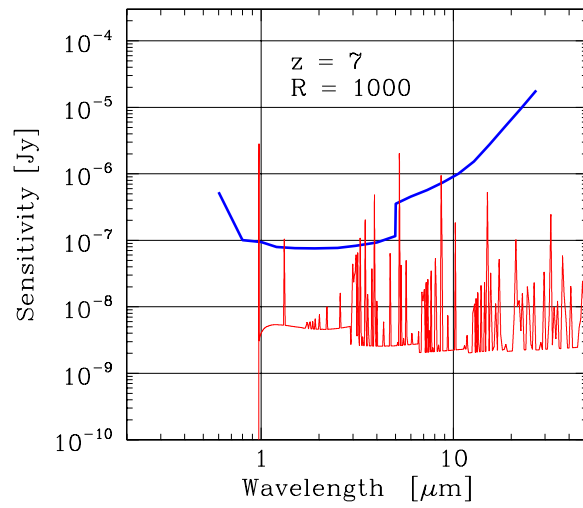
**Figure 9.** Synthetic spectral energy distribution of a  $Z=10^{-3}Z_{\odot}$  starburst object at  $z=15$  containing  $10^6 M_{\odot}$  in massive stars (thin line) compared to the imaging limit of NGST at  $R=5$  (thick line). The NGST sensitivity refers to  $10^5$ s exposures with  $S/N=5$ .

#### 7.4. Conclusions

It is possible to discern truly primordial populations from the next generation of stars by measuring the metallicity of high- $z$  star forming objects. The very low background of NGST will enable us to image first-light sources at very high redshifts, identifying them through the Lyman break technique. Unfortunately, the relatively small collecting area of a 6m NGST will limit its capability in obtaining spectra of  $z \sim 10$  first-light sources. Thus, the discrimination between first and second generation objects may have to rely on the next generation of large ( $\sim 30$ m) ground-based telescopes.

#### ACKNOWLEDGMENTS

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**Figure 10.** Synthetic spectrum of a  $Z=10^{-3}Z_{\odot}$  starburst object at  $z=7$  containing  $10^6 M_{\odot}$  in massive stars (thin line) compared to the spectroscopic limit of NGST at  $R=1000$  (thick line). The NGST sensitivity refers to  $10^5$  s exposures with  $S/N=5$ .